

8.6A PARAMETERIZATION OF SPECTRA

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Following reception and A/D conversion, atmospheric radar backscatter echoes need to be processed so as to obtain desired information about atmospheric processes and to eliminate or minimize contaminating contributions from other sources. Various signal processing techniques have been implemented at various MST facilities to estimate parameters of interest from received spectra. Such estimation techniques need to be both accurate and sufficiently efficient to be within the capabilities of the particular data-processing system. This paper will review and compare the various techniques used to parameterize the spectra of received signals.

SIGNAL CONSTITUENTS

The received signal consists of one or more of the following;

- (1) Backscattered signal. Generally one is interested in quantifying the signal power, Doppler shift (velocity) and Doppler width of the signal spectrum. There may be one or more signal peaks in a given spectrum.
- (2) Noise. While anything other than the desired signal can be considered noise, we will exclude clutter and interference from specific sources from our definition and consider only atmospheric, cosmic and receiver noise.
- (3) Contribution to zero frequency power due to obstacles such as mountains and ocean waves. In the case of ground clutter there may be a non-fading dc component and a fading component with non-zero Doppler shift and width, the latter due to multiple phase paths from index of refraction variations and the rustling of leaves on trees. The magnitude and frequency spread of ground clutter is dependent on radar wavelength and antenna configuration. For 50-MHz systems, clutter is usually non-fading; higher frequency systems have a broader clutter spectrum. In the cases of Millstone Hill and Arecibo, antenna geometry introduces severe ground clutter contamination from antenna sidelobes. Distant ocean waves and moving vehicles can produce apparent signals of significant power and Doppler shift.
- (4) Interference from electromagnetic sources. Other transmitters with operating frequencies or harmonics at the radar frequency can produce spurious peaks or an increase in the spectral noise level. Electromagnetic interference may originate from near sources and propagate line-of-sight, or from far sources and propagate via ionospheric reflections or along atmospheric ducts.
- (5) Interference, i.e., echoes from airplanes and other scatterers of an intermittent, short period nature. Airplanes produce a characteristic dragontail-like spectrum, while rain produces a broadband spectrum which is dependent on radar wavelength. Depending on system operating parameters such as IPP, code and coherent integration time, echoes from ionospheric layers can produce spurious peaks and raise the noise level.
- (6) 60 Hz and power line harmonics. This quasi-stationary electromagnetic interference may enter the radar system at various points of transmission and reception.

(7) Signal processing effects and artifacts, i.e., pulse coding, coherent integration, finite time series. Truncations of time series and frequency domain sampling cause a spillover of clutter into other frequency bins across the spectrum (SATO and WOODMAN, 1982). Coherent integration has a $\sin X/X$ transfer function which distorts the power and width of the signal spectrum. Imperfect implementation of complementary codes can produce ghost echoes.

(8) Instrumental effects, i.e., beam and shear broadening. A finite antenna beam width results in a broadening of the spectrum. Spectral broadening due to wind shear is a function of available height resolution which depends on pulse width and coding.

(9) Ducting, i.e., multiple ray propagation from main or sidelobes along atmospheric waveguides such as temperature inversions.

Figure 1 taken from SATO and WOODMAN (1982) illustrates some of the spectral characteristics discussed above. One will note a strong dc component as well as a fading clutter component which is symmetric about zero frequency and spreads over the lowest frequencies. The secondary peak at 10.1 km is a ghost peak due to code imperfections; a similar peak occurs at higher altitudes due to ocean clutter. Figure 2, courtesy of P. K. Rastogi, is a Doppler profile taken at Millstone Hill. Two interesting features of this profile besides the signal are power line spikes at 60 Hz and harmonics and a tropospheric duct which emulates the signal profile.

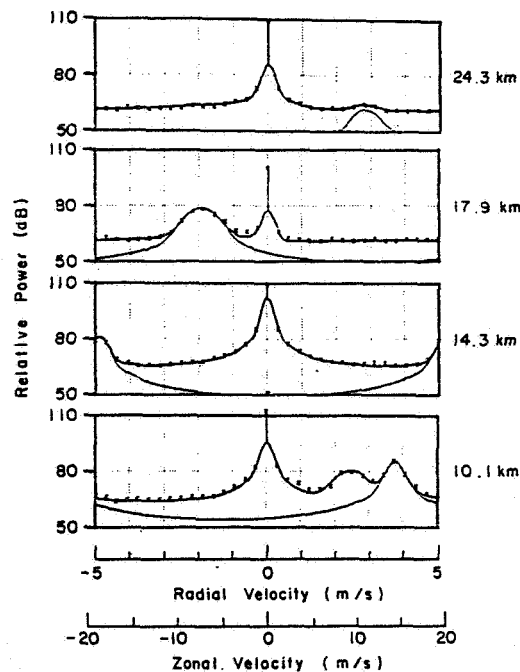


Figure 1. Examples of theoretical curves fitted at four different altitudes. The dotted, the thick and the thin line stand for the data, the fitted spectra, and the CAT contribution, respectively. The vertical line at zero Doppler shift shows the unfading clutter component (from SATO and WOODMAN, 1982).

SPECTRAL CALCULATION AND PREPARATION

At most MST radar facilities, either the power spectrum or the corresponding autocorrelation function (ACF) of the returned signal is computed. ACF calculations have been performed historically at incoherent-scatter and meteor-scatter radar facilities due to their computational ease with limited digital hardware and are to be discussed elsewhere. Power spectra of the returned signal are generally computed via fast Fourier transform (FFT) algorithms either on-line or during off-line processing.

Before taking the FFT of the sampled signal, the dc component of the time series may be filtered out by subtracting the mean value, and an appropriate weighting function, e.g., Hanning (cosine) window, can be applied to minimize truncation effects; both of these are performed at Poker Flat. Additionally, phase errors in quadrature demodulation and differential amplification of the two (i.e., complex) channels of the signal can be compensated by calculation of a covariance matrix based upon the statistical independence and the equipartition of average power over a long-term interval of the two channels; this scheme has been implemented at SOUSY (SCHMIDT et al., 1979).

After taking the FFT of the time series and computing power spectra, spectra may be smoothed by taking a running mean over the spectra to minimize fluctuations. The averaging (incoherent) of several time contiguous spectra yields a similar result. At Millstone Hill, a recursive despiking and notching routine is applied to the spectra before a recursive smoothing (running mean) routine is used. Despiking consists of replacing a spike in the spectrum by the average of its two adjacent points, followed by a notching and filling in from adjacent frequency bins of certain interfering frequencies (e.g., 60 Hz).

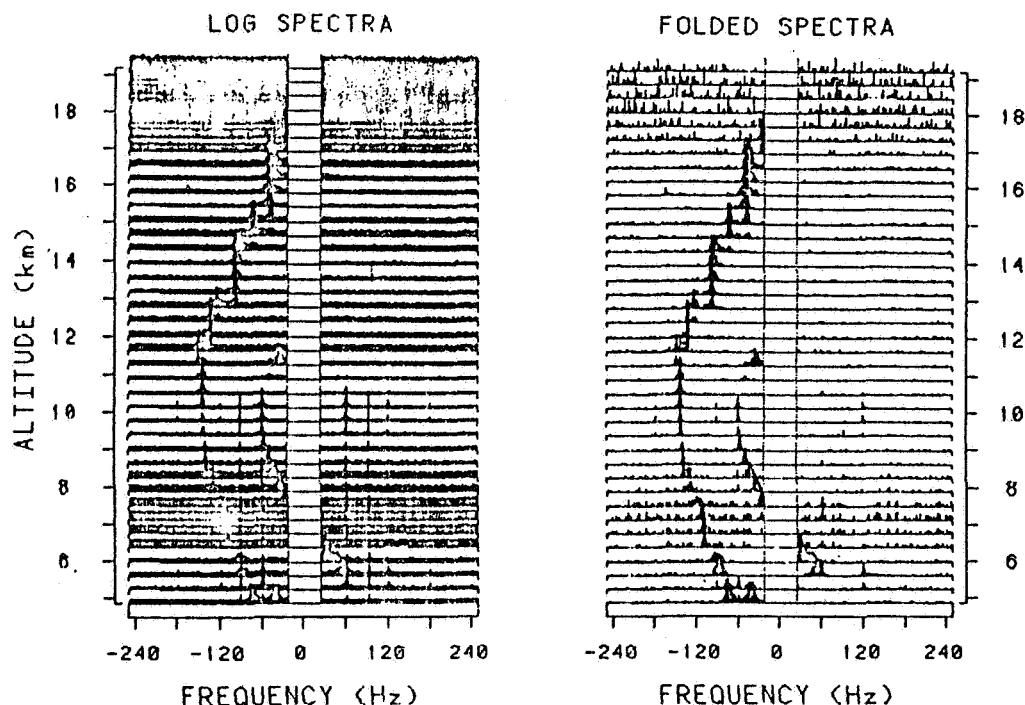


Figure 2. Profile of spectra from Millstone Hill (courtesy P. K. Rastogi).

PARAMETER ESTIMATION

In the following section we will discuss the variety of techniques used to eliminate undesirable interference and clutter and to estimate the desired signal parameters.

Contributions to the dc or zero frequency of the power spectrum originate from ground clutter, system biases, noise and possibly signal. During transmission and reception, system dc can be eliminated by a 180° flip from pulse-to-pulse and subsequent coherent integration. During spectral parameterization any one of the following schemes is useful for eliminating dc contributions from non-fading clutter and system biases:

- (1) Notching out the zero frequency and averaging the two adjacent bins to interpolate a new zero frequency value;
- (2) Before FFT, subtracting the long term mean from the time series of returned echoes;
- (3) After FFT, subtracting the coherent average (phase preserved) at zero frequency from the incoherent average of several power spectra.

The second and third techniques are equivalent and yield information (i.e., values of signal and noise at zero frequency) that may be lost by the first in the presence of fading clutter.

Treatment of non-fading clutter has been discussed above. Fading clutter is either non-existent or minimal at 50 MHz. At higher frequencies and for particular antenna geometries, fading clutter is significant, rivaling or surpassing the signal in power. At Millstone Hill long FFTs (256 or 512 pts) are computed to separate clutter from signal, with the zero and nearby frequencies subsequently notched out. Non-fading clutter is generally symmetric; a symmetric part subtraction of the spectrum can eliminate most all of it. However, fading clutter can have a slight Doppler shift resulting in a slight asymmetry. At Arecibo a sophisticated approach of using a nonlinear (N-L) least squares fit to the fading clutter (power, Doppler shift, width, form: Gaussian or Lorentzian) and ocean clutter (power, Doppler shift, width) as well as to the signal has been implemented. The forementioned symmetric subtraction scheme is used at Arecibo to obtain initial values for the N-L least squares fit.

Interference, both electromagnetic and from other sources, introduces spurious peaks or spikes and raises the noise level of the spectrum. Spikes can be removed by notching the spike and averaging over adjacent values and/or filtered out by taking a running mean across the spectrum. Depending on the parameters of the interfering source, e.g., duration bandwidth, and the sampling parameters, e.g., IPP and coherent integration time, interference can be smeared across the spectrum. Interference from other transmitters is generally non-synchronized with the pulse repetition frequency (PRF) of the probing system and not much energy is contained within their transmissions unless the interfering transmitter is strong or nearby. During the ALPEX experiment in 1982, signals from most altitudes were contaminated by an interfering harmonic of a distant transmitter in Canada; the interference was eliminated by an appropriate high pass filter in the front end of the 50-MHz receiver (W. Ecklund, personal communication, 1983). Airplanes have a characteristic dragontail-like spectral signature spreading across many frequency bins which varies in time as the airplane orientation and position changes. A scheme implemented at Poker Flat to eliminate airplane interference checks the total power in the spectrum with previous total power values for that height. Should the total power exceed the previous value by a threshold factor, that spectrum and following ones are

skipped until the power returns to the uncontaminated value (CLARK and CARTER, 1980).

Power line interference at 60 Hz and its harmonics can be eliminated during transmission by an alternating 180° phase flip of the transmitted pulses and subsequent summation/subtraction of the samples. Proper selection of PRF and coherent integration time can cause 60-Hz interference to fall at a null of the coherent integration filter transfer function or to be folded back into a given point of the spectrum, e.g., near zero frequency. Should the above tactics be inapplicable at the time of spectral sampling, power line harmonics, which occur at known points in the spectrum, can be notched and filled in as done at Millstone Hill.

Spectral broadening due to signal processing and instrumental effects can be represented by transfer functions, which differ from an ideal delta sampling function. Coherent integration, for example, has a $\sin X/X$ transfer function, where $X = \pi fT$ and f is the frequency in Hz. Attenuation of the power at a given spectral point can be compensated for by applying a spectral weighting function as proposed by CLARK and CARTER (1980). Recently, HOCKING (1983) has determined the spectral broadening effects due to finite beam width and wind shear and has deconvolved measured spectra from the mesosphere with the calculated transfer functions so as to determine signal spectral widths due to turbulence. At Arecibo, SATO and WOODMAN (1982) have applied an N-L least-squares fit of a measured spectrum to a theoretical one. To compensate for signal processing effects on the measured spectrum due to coherent integration, finite time series and frequency domain sampling, the theoretical spectrum is similarly distorted. This procedure, similarly done in fitting incoherent scatter ACFs at mesospheric heights and higher, frees the estimated parameters from processing biases.

Having recognized and eliminated or compensated for undesirable contributions to a given spectrum, we proceed to a discussion of estimation of noise and signal in a given spectrum calculation. While backscattered echoes are being collected, a noise profile can be made without the transmitter or a "noise" height can be sampled during each IPP. The former technique, while measuring cosmic and receiver noise, does not include noise contributions by the transmitter. The latter procedure, while including transmitter noise effects, assumes there is no measurable signal at a given range of altitude. This procedure requires additional data acquisition and storage of samples from the noise heights, and, like the first, does not give a value of the atmospheric noise at a given height.

Noise estimation from a given spectrum is based on the assumption that the signal is confined to the narrow part of the spectrum and the noise power is evenly distributed across the spectrum. Noise power unit frequency cell is estimated from either:

- (1) The lowest value of spectrum;
- (2) The average from outer wings of spectrum, where no signal is assumed to be present;
- (3) Dividing the spectrum into segments and using the average power from those segments which have the lowest average values.

Subsequently, the noise power is estimated by multiplying this noise per cell value by the number of frequency cells. All three methods are subject to biases of insufficient sampling.

A novel and perhaps more objective noise estimation technique first

described by HILDEBRAND and SEKHON (1974) and used at Poker Flat is based on the statistics of a Gaussian random variable. Specifically, the ratio of the variance to the square of the mean of the spectrum is computed.

$$R_n = \left\{ \frac{\sum_{i=1}^n S_i^2 - 1/n \left(\sum_{i=1}^n S_i \right)^2}{\left\{ 1/n \left(\sum_{i=1}^n S_i \right)^2 \right\} 1/M} \right\}$$

where S_i , $i = 1, n$ are the n smallest values of a spectrum obtained from the average of M sequential spectra (A. C. Riddle, private communication, 1983). An estimate of the noise level is determined from the mean value of the N smallest values of the spectrum for which $R_n > 1$, $n > N$. In any procedure of noise estimation from the spectrum, spectral leakage of signal and clutter to other frequencies must be compensated for in order to obtain an unbiased noise estimate. Noise estimation from the spectrum includes all contributions (cosmic, atmospheric, system, interference) and provides a suitable value for signal/noise (S/N) determination.

Following determination of the noise level, one can proceed to estimate the signal parameters of interest, usually power, Doppler shift, and width. A simple but crude approach to signal estimation is to attribute the largest peak to the signal, using the peak value as the signal power and its frequency as the Doppler shift. This method, while fast and computationally simple, is subject to biases with the frequency resolution as good as the spectrum's. Furthermore, one must ascertain that peaks from non-signal sources have been eliminated or recognized and compensated for.

The most common method of estimation of signal parameters is the calculation of the first 3 spectral moments. In general the noise level is calculated and subtracted out. Some signal-to-noise criterion is used to discard weak and uncertain signals; if the peak-to-noise ratio is below some threshold level, that spectrum is eliminated before the moment calculations. Then the spectral moments are calculated for some frequency band centered about the peak of the spectrum. The signal power, velocity and width are characterized by the zeroth, first and second moments of the band limited spectrum, respectively. At Poker Flat, a window centered at the largest peak in the spectrum is set for moment calculations; starting at the center peak, all contiguous points with values greater than the noise level are attributed to the signal. At Millstone Hill the peak of the spectrum is found and some window is chosen; then the 1st moment is recursively calculated, with a window centered at the value of the 1st moment of the previous iteration. The number of iterations and window width may be fixed or may be varied so that the window size converges to a width where signal is present. Subsequent to the choice of a window the first 3 spectral moments are calculated. In general, estimation of signal parameters by moment calculations is a straightforward method, can be performed on-line in real time, and provides unbiased estimates over the ensemble average. In cases when true signal widths are narrower than the frequency resolution of the spectrum, or when signal strength is weak and comparable to noise power fluctuations, the signal velocity is biased towards the nearest frequency bin.

A powerful but computationally intensive technique for parameter estimation of the signal is to fit the measured spectrum to a theoretical one using an N-L (nonlinear) least squares fitting routine. Such a method has been implemented at Arecibo by SATO and WOODMAN (1982), where computed spectra of atmospheric echoes are Fourier transformed into ACFs and subsequently fitted to a theoretical ACF. Time domain fitting has certain computational advantages over spectral domain fitting. Either eight or eleven parameters are fitted to the ACF:

- 1 zero frequency (dc) component, i.e., non-fading clutter;
- 2-5 power, width, Doppler shift, form of fading clutter;
- 6-8 power, width, Doppler shift of signal;

9-11 power, width, Doppler shift of secondary peak due to ghost echo, ocean clutter, or secondary signal.

An N-L squares fitting method in the spectral domain has been used to fit three signal parameters (power, velocity, width) to measured spectra from Jicamarca by CORNISH et al. (1982). The N-L least squares approach offers the advantages of a frequency resolution which is better than the sampling interval of the spectrum, the estimation of spectral widths even as narrow as a frequency cell, and the inclusion of contaminating effects, e.g., clutter, in the actual fitting and estimation of signal parameters. The biggest drawback of the N-L least squares approach is that it is computationally intensive; at Arecibo a profile of 150 heights collected over a minute's duration requires one minute of post-collection processing with an array processor. Furthermore, the nonlinear fitting necessitates constraints and initial values; the former may be unduly restrictive at times, the latter requires prefitting guesses obtained by visual inspection, computer algorithms such as moment calculations, or comparison to other wind measurements such as radiosonde data.

So far we have considered parameter estimation of the signal and clutter and interference elimination only for a single spectrum. There exist temporal and spatial continuities in a time series of spectral profiles which can be employed. Certain a priori information such as the occurrence of power line radiation at 60 Hz and harmonics or the characteristics of fading clutter (e.g., magnitude, persistence in time and diminution with height) is useful in minimizing contaminating effects. Echoes backscattered from the atmosphere exhibit continuity in time and height that can restrict the search of signal peaks to a certain part of the spectrum. Doppler tracking from height to height uses continuity arguments for establishing a window to search for a signal within based on Doppler shift of an adjacent height; such schemes are employed at Arecibo and Millstone Hill. Furthermore, aliased spectra can be unwrapped if height continuity arguments show that they are indeed aliased. A full profile of spectra can provide additional information about the spectra such as the occurrence of ducts as seen in Figure 2; without such continuity arguments and confusion over two signal-like peaks would arise.

Temporal continuity provides initial guesses for the estimation of signal values. At Arecibo initial guesses to the N-L least squares routine are computed from a weighted average of previous fitted values at a given height. Temporal and height continuity restrictions are dependent on the temporal and height resolution of the probing radar system in relation to the temporal and height variations of the scattering atmosphere. While temporal and height continuities confine a signal window to a part of the spectrum, it is still possible for the algorithm used for parameter estimation of the signal to lock onto some spurious peak or interference. Such "wandering" effects can be checked and minimized. One proposed algorithm checks minima between peaks, attributes minima above the noise level to a multi-peaked signal, and combines these above-noise-level peaks and valleys in subsequent moment calculations (A. C. Riddle, private communication, 1983). In the future, image processing techniques may be helpful in tracing backscatter echoes in height and time.

The selection of a particular parameter estimation technique is determined by the information desired and the capabilities of the particular radar and processing systems to obtain it. On the one hand, one may want highly accurate and precise estimates of spectral widths from atmospheric backscatter to study atmospheric turbulence. On the other hand, precision may be sacrificed in order to obtain a continuous long term series of the 3-D wind vector over many heights for studies of planetary waves and longer period oscillations. The need and availability of on-line and post-collection processing, limitations of computer memory and speed, availability of array processors and special devices and development of general use and special use software are considerations in the

selection and implementation of a parameter estimation technique.

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